EF03 EW Physics:
Heavy flavor and top quark physics

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EF Restart workshop, September 3, 2021

Top and Heavy Flavor Physics

- Prospects for precision measurements (HL-LHC, FCC, ILC, muon collider,...):
  - top quark properties: mass, couplings
  - study of rare processes: single top, ttZ, ttW, tZq, tttt, FCNC, ...
  - precision measurements of a wide variety of observables and in new kinematic regimes: spin correlations, polarization, boosted top, ...
- Joined studies:
  - M_{top} in Global Electroweak fits (with EF04)
  - Top quark couplings and global EFT fits (with EF04)
  - Top and HF in PDF fits: extraction of gluon PDF, alphas, ... (with EF06)
- Prospects for HF physics (b,c,s) at future colliders
  - Full pattern of quark couplings
- Status of predictions and prospects for theory improvements:
  - Interpretation of m_{top}, new ideas for m_{top} measurements
  - Higher order QCD and EW corrections

Opportunities for additional contributions in all areas!

Talk in parallel sessions

Highlights of EF03 activities: m_{top}

- Optimizing top-quark threshold scan using genetic algorithm: Aleksander Filip Zarnecki, Kacper Nowak LoI, paper: https://arxiv.org/abs/2103.00522
- Limits on Precision Top Mass Measurements at HL-LHC: Stephen Wimpenny
- Measurement of the top quark mass at the ILC: Esteban Fullana , Juan Foster, Frank Simon, Marcel Vos LoI
- Top quark mass measurements and their interpretations: Andre Hoang
- Energy Peak and Its Implications on Collider Phenomenology: Top Quark Mass Determination and Beyond: Kaustubh Agashe, Roberto Franceschini, and Doojin Kim LoI

Presented at this workshop:

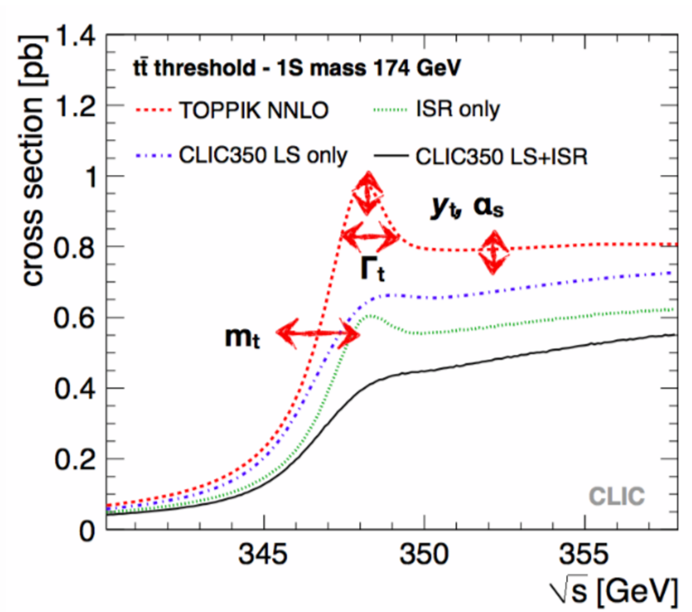
- Top and HF studies at linear colliders: Roman Poeschl
- New ideas for top quark mass measurements: Kaustubh Agashe

LoI: Letter of Interest

Highlights of EF03 activities: m_{top}

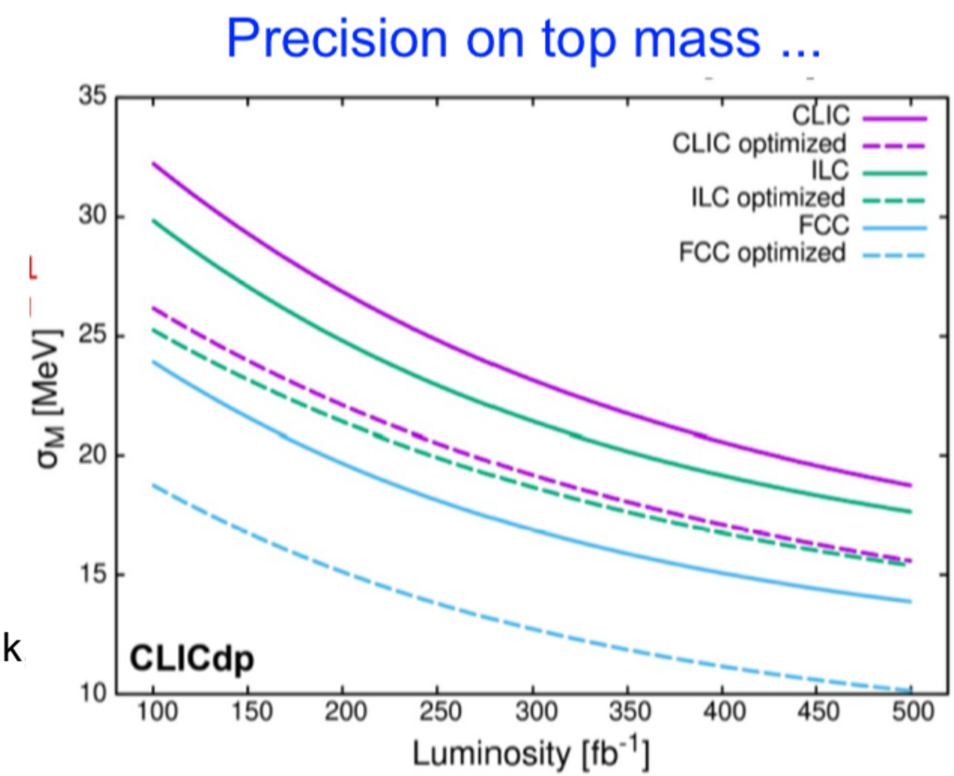
- Top and HF studies at linear colliders: Roman Poeschl

Optimisation of threshold scan using “Non dominated sorting **genetic algorithm**” *arxiv: 2103.00522*



- Effects of some parameters are correlated:
- Dependence on Yukawa coupling rather weak
- Precise external α_s helps

<u>Kacper Nowak, Aleksander Filip Zarnecki</u>



Highlights of EF03 activities: m_{top}

- New ideas for top quark mass measurements: Kaustubh Agashe

b-jet energy peak method:

- implementation on run 1 data in CMS PAS TOP-15-002:

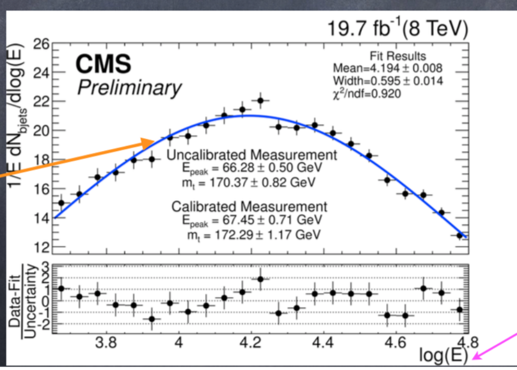
$$m_t = 172.29 \pm 1.17\ (\text{stat.}) \pm 2.66\ (\text{syst.})\ \text{GeV}$$

- Complementary (next slide) to other methods (error~1 GeV)
- Sources of error: JES uncertainty; modeling of top p_T

use B-hadron decay length (next)

higher-order (theory) calculation (KA, Franceschini, Kim, Schulze: 1603.03445; see also Ravasio, Jezo, Nason, Oleari: 1801.03944 and 1906.09166)

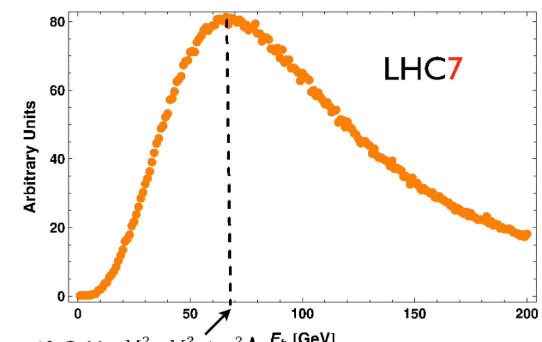
fitting function (see later)



note!

$$E_b^{\text{rest}} = \frac{M_t^2 - M_W^2 + m_b^2}{2M_t}$$

modified vs. massless



$$68\ \text{GeV} = \frac{M_t^2 - M_W^2 + m_b^2}{2M_t}\ !$$

how to "extend" it to B-hadron decay length (correlated with bottom quark energy): circumvent JES uncertainty, "replaced" by hadronization model/fragmentation function (theory improvement possible?)

B-decay length method:

$$G^{\text{fit, us}}\left(L_B; \underbrace{E_b^{\text{rest}}, w}_{\text{parameters}}\right) \approx \int dE_B \int dE_b \frac{1}{N(w)} \exp\left[-w\left(\frac{E_b}{E_b^{\text{rest}}} + \frac{E_b^{\text{rest}}}{E_b}\right)\right] \times D\left(\frac{E_B}{E_b}; E_b\right) \frac{m_B}{c\tau_B^{\text{rest}} E_B} \exp\left(-\frac{L_B m_B}{c\tau_B^{\text{rest}} E_B}\right)$$

observable

(similar procedure to b-jet energy-peak method: different observable and (double) convolution in fitting function)

$G^{\text{fit}}\left(L_B; E_b^{\text{rest}}, w\right) \rightarrow$ fitting function for observed decay length (L_B) distribution

Highlights of EF03 activities: Quark polarizations and spin correlations

- Quark polarization measurements: from the Standard Model to characterizing New Physics: Mario Galanti, Andrea Giammanco,Yuval Grossman, Yevgeny Kats,Emmanuel Stamou, Jure Zupan LoI
- Top Quark and BSM Interactions at the HL-LHC and HE-LHC: Andreas Jung, Alexander Moreno Briceno LoI

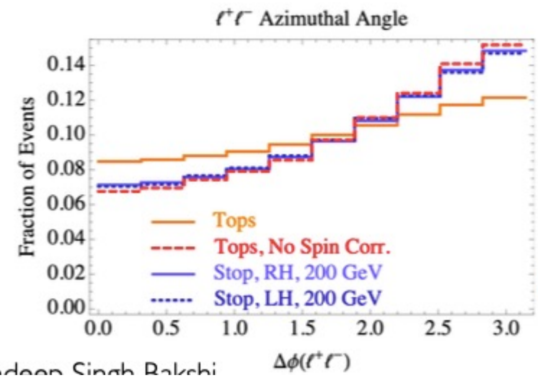
Presented at this workshop:

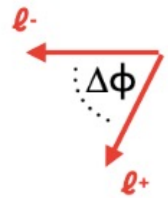
- Top quark spin correlations at the LHC: Amandeep Singh Bakshi

Highlights of EF03 activities: Quark polarizations and spin correlations

- Top quark spin correlations at the LHC: Amandeep Singh Bakshi

  - Very sensitive to BSM physics (s-channel dark matter : more spin correlation, new scalars : less spin correlation)

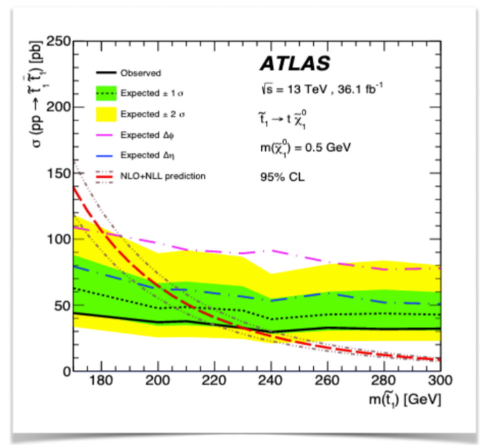




10.1007/JHEP08(2012)083

Plans for Snowmass study

- Set limits in the SUSY top corridor using the spin correlation based DNN.
- Extend phase space beyond stealth corridor region and also study other partners to the top.
- Consider different uncertainty scenarios (full Run2, upcoming Run3 and the HL-LHC) and the impact of major systematics on the limits.
- Our HL-LHC analysis has been pre-approved.
- Could expand into spin density matrix measurement at other colliders/machines: 100 TeV pp, e+e-, muon colliders.



CERN-EP-2019-034, ATLAS

Highlights of EF03 activities: bb,cc,ss production at lepton colliders

- Electroweak Heavy Flavour (b,c,tau) at the FCC-ee: Patrizia Azzi, Alain Blondel, Mogens Dam, Patrick Janot, Stéphane Monteil, and Guy Wilkinson LoI
- Electroweak couplings of heavy and light quarks at future linear e+e− colliders: Roman Poeschl, Marcel Vos LoI

Presented at this workshop:

- Top and HF studies at linear colliders: Roman Poeschl

Highlights of EF03 activities: bb,cc,ss production at lepton colliders

- Top and HF studies at linear colliders Roman Poeschl

Why study lighter quarks?

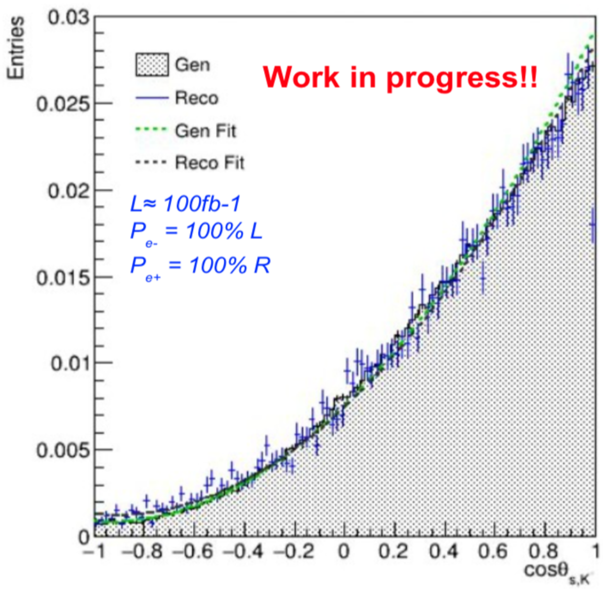
- Deviations from SM of the order of a few %
  - Effects measurable already at 250 GeV
  - Effects amplified by beam polarisations
  - Effects for tt, bb and cc (and other light fermions)
- One concrete example for importance to measure full pattern of fermion couplings
  - Full pattern only available with beam polarisation

Examples: GUT inspired models Higgs unification model; Randall-Sundrum model modify light quark couplings

New: ee->ss @ 250 GeV

Y. Okugawa, F. Richard, A. Irles, R.P.

Full simulation with ILD s/w framework



- This is just an appetiser!
- Analysis is very early stage
  - Full simulation and reconstruction but preselection based on MC truth
  - Analysis will consolidate during Snowmass process!
- Backbone is selection of charged Kaon
  - Strict requirement that charged Kaon with PK > 10GeV is leading particle in jet
- Need to control backgrounds from ee->uu and ee->dd
- Will complete picture on ee->qq
  - The rest is uu/dd that will be insdistinguishable and will have to be treated together
- Excellent benchmark for detector
  - “Particle ID is King”

Highlights of EF03 activities: bb,cc,ss production at lepton colliders

- Top and HF studies at linear colliders Roman Poeschl

HQ at ILC/CLIC – Overview on status of analyses

	$\sqrt{s}$-250 GeV	Threshold	Continuum (≥ 380 GeV)	Comment
ee->tt (electroweak)	N/A	Not covered	Not covered	• ILC/CLIC Papers exist • CLIC380 close(r) to threshold • ee->tt fully hadronic is not covered (and difficult!) • ee->tt semi-leptonic needs re-assessment of systematic uncertainties
ee->tt (top mass)	N/A	Not covered	Covered	• Many studies and papers exist • However uncovered aspects (AFB, at threshold, polarisation effects, ... • Top mass in continuum requires full sim. study
ee->bb	Covered		Covered	• 250 GeV: paper publication in progress • 500 GeV freshly started
ee->cc	Covered		Covered	• 250 GeV: paper publication in progress • 500 GeV freshly started
ee->ss	Covered		Not covered	• 250 GeV: freshly started

The picture is likely to be incomplete! Please let me know if everything is missing

Highlights of EF03 activities: Couplings and EFT fits (with EF04)

- ILC: EFT fit for top and bottom EW couplings: Gauthier Durieux, Martin Perello , Roman Poeschl
- The top quark (EW) couplings at future colliders: Marcel Vos
- Electroweak couplings of heavy and light quarks at future linear e+e− colliders: Roman Poeschl, Marcel Vos LoI
- Novel constraints on EFT in the top sector: Alexander Grohsjean, James Keaveney, LoI, paper: James Keaveney, https://arxiv.org/abs/2107.01053

Presented at this workshop:

- Global fits for top operators: Eleni Vryonidou
- EFT studies in the top quark sector (and beyond): Nuno Castro

Highlights of EF03 activities: Top EFT fits

- EFT studies in the top quark sector (and beyond): Nuno Castro

Effective field theory in the top quark sector

$t\bar{t}$ operators

- Observables: Rate, Distribution, Asymmetries, Polarization, Spin correlation

Linear

$O_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu}$

$O^{1,8}_{Qq} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$

$O^{3,8}_{Qq} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i)$

$O^{8}_{tu} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i\gamma^\mu T^A u_i)$

$O^{8}_{td} = (\bar{t}\gamma^\mu T^A t)(\bar{d}_i\gamma_\mu T^A d_i)$

$O^{8}_{Qu} = (\bar{Q}\gamma^\mu T^A Q)(\bar{u}_i\gamma_\mu T^A u_i)$

$O^{8}_{Qd} = (\bar{Q}\gamma^\mu T^A Q)(\bar{d}_i\gamma_\mu T^A d_i)$

$O^{8}_{tq} = (\bar{q}_i\gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t)$

Quadratic

$O^{1,1}_{Qq} = (\bar{Q}\gamma_\mu Q)(\bar{q}_i\gamma^\mu q_i)$

$O^{3,1}_{Qq} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i\gamma^\mu \tau^I q_i)$

$O^{1}_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}_i\gamma^\mu u_i)$

$O^{1}_{td} = (\bar{t}\gamma^\mu t)(\bar{d}_i\gamma_\mu d_i)$;

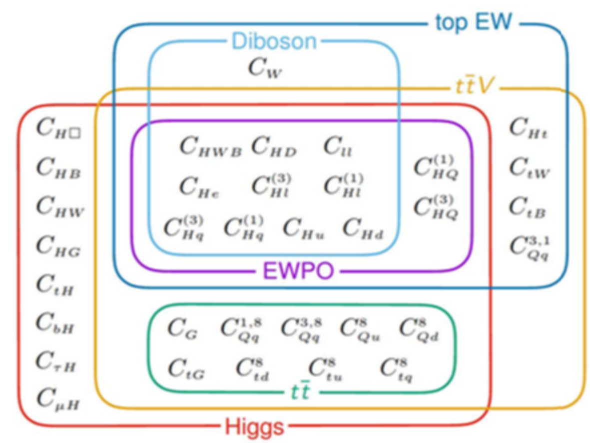
$O^{1}_{Qu} = (\bar{Q}\gamma^\mu Q)(\bar{u}_i\gamma_\mu u_i)$

$O^{1}_{Qd} = (\bar{Q}\gamma^\mu Q)(\bar{d}_i\gamma_\mu d_i)$

$O^{1}_{tq} = (\bar{q}_i\gamma^\mu q_i)(\bar{t}\gamma_\mu t)$;

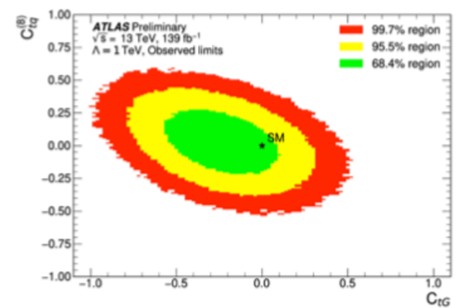
Four-fermion in V/A basis

$$4C^{u,8}_{VV} = C^{1,8}_{Qq} + C^{3,8}_{Qq} + C^{8}_{tu} + C^{8}_{tq} + C^{8}_{Qu}$$
$$4C^{u,8}_{AA} = C^{1,8}_{Qq} + C^{3,8}_{Qq} + C^{8}_{tu} - C^{8}_{tq} - C^{8}_{Qu}$$
$$4C^{u,8}_{AV} = -(C^{1,8}_{Qq} + C^{3,8}_{Qq}) + C^{8}_{tu} + C^{8}_{tq} - C^{8}_{Qu}$$
$$4C^{u,8}_{VA} = -(C^{1,8}_{Qq} + C^{3,8}_{Qq}) + C^{8}_{tu} - C^{8}_{tq} + C^{8}_{Qu} .$$



[slide by Cen Zhang]

$t\bar{t}$ operators: differential measurements



Also studied: single top and $t\bar{t}$V operators

Focus changing to global fits

Vilson coefficient	Marginalised 95% intervals Expected	Marginalised 95% intervals Observed	Individual 95% intervals Expected	Individual 95% intervals Observed	Global fit [2105.00006]
C_{tG}	[-0.44, 0.44]	[-0.68, 0.21]	[-0.41, 0.42]	[-0.63, 0.20]	[0.007, 0.111]
$C^{(8)}_{tq}$	[-0.35, 0.35]	[-0.30, 0.36]	[-0.35, 0.36]	[-0.34, 0.27]	[-0.40, 0.61]

Highlights of EF03 activities: Top EFT fits (jointly with EF01, EF04)

- Global fits for top operators: Eleni Vryonidou

Global EFT fits in top physics

Future directions (2)

Future colliders:

- Unlike the Higgs and EW sectors, limited work on HL-LHC, FCC-hh projections for top operators, need for global analyses
- Truly global fits for future colliders as typically only subsets of operators considered
- Combination of top+Higgs for future colliders, including 1-loop effects
- Systematic comparison prospects of different future colliders (ILC, FCC-ee, CEPC and different energies), using a common setup and common set of operators

Highlights of EF03 activities: Couplings and EFT fits (jointly with EF04)

Presented at EF03/EF04 workshop in Jan. 2021: https://indico.fnal.gov/event/46514/

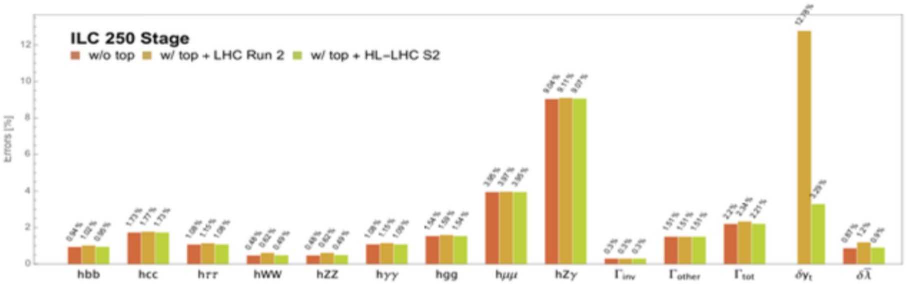
- The top quark (EW) couplings at future colliders: Marcel Vos

Grand, global SM EFT fits

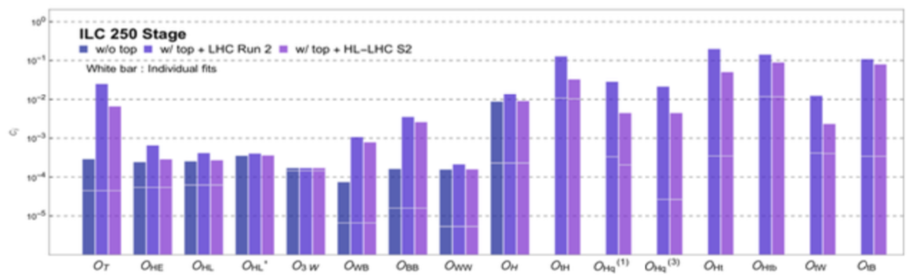
S. Jung. J. Lee, M. Perelló, J. Tian, M.V., arXiv:2006.14631

Top and bottom EW couplings affect 250 GeV Higgs fit considerably

Physical Higgs couplings largely shielded from extra degrees of freedom



Limits on Wilson coefficients are affected by inclusion of top operators, even with the most optimistic HL-LHC prospects



[See also S. Jung]

Snowmass EF03/04, 29/01/2021 15 marcel.vos@ific.uv.es

Highlights of EF03 activities: Top and HF in PDFs (with EF06)

- Constraining heavy flavor PDFs at hadron colliders: Marco Guzzi, Timothy Hobbs, Pavel Nadolsky, Laura Reina, Doreen Wackeroth, Keping Xie, C.-P. Yuan LoI

Presented at this workshop:

- The role of top quark observables in PDFs: CT: Marco Guzzi; MSHT: Robert Thorne; NNPDF: Emanuele Nocera
- Simultaneous extraction of alphas and m_{top} from tt differential distributions: Matthew Lim
- Experimental and phenomenological issues relevant for PDF extractions from top differential distributions Amanda Cooper Sarkar

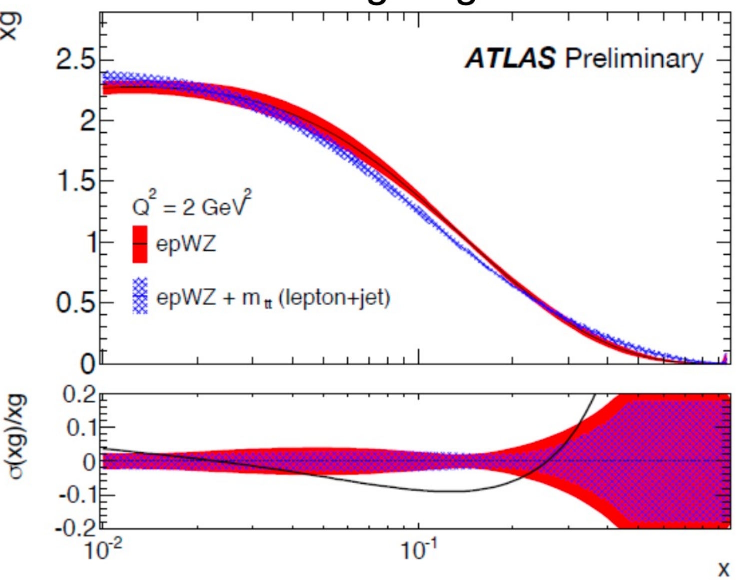
Highlights of EF03 activities: Top in PDFs (jointly with EF06)

- PDF fitting t-tbar data- experimental considerations: Amanda Cooper Sarkar

The importance of the correlation of systematic uncertainties:

- between data points within a spectrum
- between different spectra from a single analysis
- between different spectra from different analyses, different processes

The most constraining top distributions are p_T^t , y_t y_{ttbar}, m_{ttbar} and they mostly constrain the high-x gluon



$$\chi^2 = \sum_{ik}\left(D_i - T_i(1-\sum_i \gamma_{ij}b_j)\right) C^{-1}_{\text{stat},ik}(D_i, D_k)\left(D_k - T_k(1-\sum_i \gamma_{kj}b_j)\right) + \sum b_j^2$$

he treatment of correlated systematics as nuisance parameters means that they can ıtroduce correlated shifts in the predictions. Examining the shifts due to these 3 sources hows that the m_{ttbar} spectrum induces an opposite shift to the other three spectra, when ıe spectra are fitted separately. When fitting together the shifts are forced to be the ame **---if 100% correlation is assumed between the spectra**. E.g. the common uisance parameter for the Parton Shower uncertainty when fitting p_T^t and m_{ttbar} ›gether is -0.32 ± 0.10, which suits neither spectrum.

10

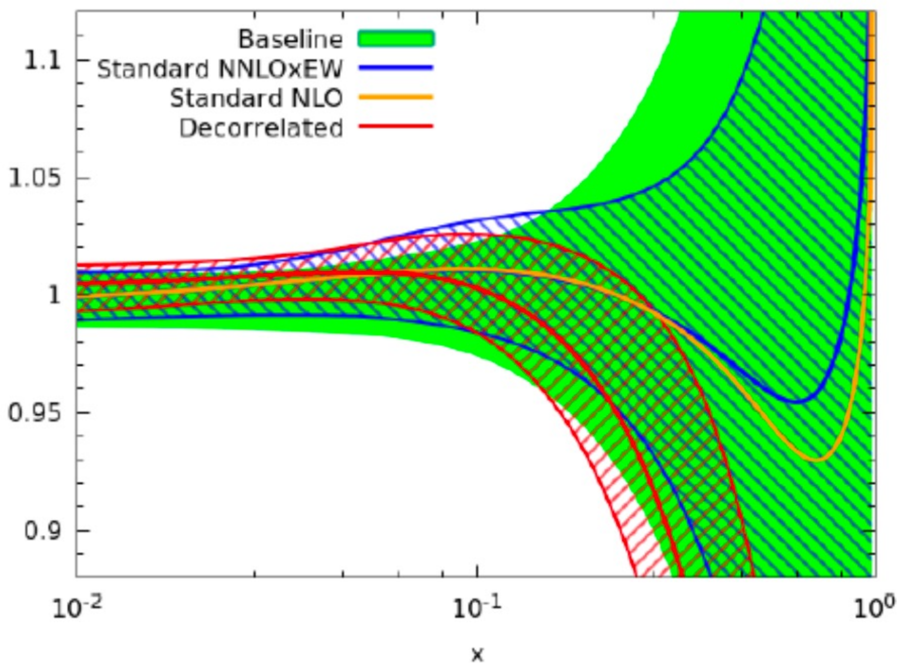
The effect of decorrelation is dramatic for the p_T^t and m_{ttbar} spectra, now that the shifts are allowed to be different. (The separate nuisance parameters are -0.47 for pt and +0.10 for mtt). The resultant χ2 is close to the sum of the χ2 of the separate fits (11.3)

Highlights of EF03 activities: Top and HF in PDFs (jointly with EF06)

- PDF fitting t-tbar data- experimental considerations : Amanda Cooper Sarkar

But for the arxiv:1909.10541 study decorrelating parton shower between all 4 spectra and using decorrelation within the rapidity spectra we see that the effect can be larger than the NLO to NNLO difference.

Comparing theoretical precision to decorrelation



- Most useful to present information on correlated uncertainties
- Naming convention for source of systematic uncertainties.
- How about inter-data-set correlations: not yet taking into account in PDF fits

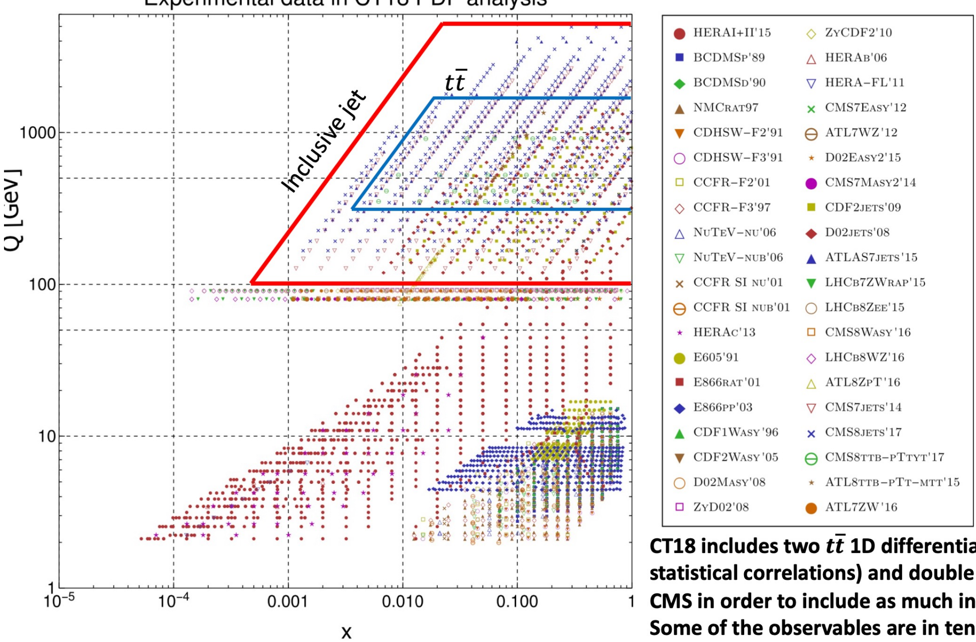
If we want 1% accuracy on PDFs this matters!

Highlights of EF03 activities: Top in PDFs (jointly with EF06)

- The role of top quark observables in PDFs: CT: Marco Guzzi

$t\bar{t}$ production kinematics in CT18

Experimental data in CT18 PDF analysis



Jet and $t\bar{t}$ complement each other in the kinematic plane. They impact the gluon PDF at large x. Important to disentangle the effect due to jet production and top-quark data.

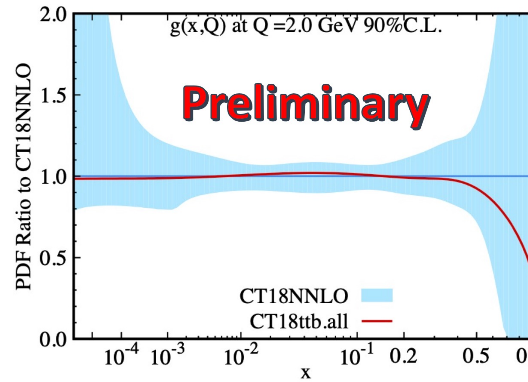
Top and jet Data in CT18

Top-quark
1511.04716 ATLAS 8 TeV tT pT diff. distributions
1511.04716 ATLAS 8 TeV tT mtT diff. distributions
1703.01630 CMS 8 TeV tT (pT , yt) 2d diff. distrib.

Jet production
1406.0324 CMS incl. jet at 7 TeV with R=0.7
1410.8857 ATLAS incl. jet at 7 TeV with R=0.6
1609.05331 CMS incl. jet at 8 TeV with R=0.7

CT18 includes two $t\bar{t}$ 1D differential observables from ATLAS (using statistical correlations) and double differential measurements from CMS in order to include as much information as possible. Some of the observables are in tension with each other.

Global fit: Impact from 13 TeV ATLAS+CMS ttbar data:




```
ATL mtt  DATA SET 520 ;  chi^2/N = 1.42643
ATL ytt  DATA SET 521 ;  chi^2/N = 1.05387
ATL HTtt DATA SET 522 ;  chi^2/N = 1.67374
ATL pTt1 DATA SET 523 ;  chi^2/N = 1.29656
ATL pTt2 DATA SET 524 ;  chi^2/N = 1.55261
CMS mtt  DATA SET 525 ;  chi^2/N = 2.96862
CMS pTt  DATA SET 526 ;  chi^2/N = 2.83397
CMS yt   DATA SET 527 ;  chi^2/N = 0.62119
CMS ytt  DATA SET 528 ;  chi^2/N = 0.52401
```

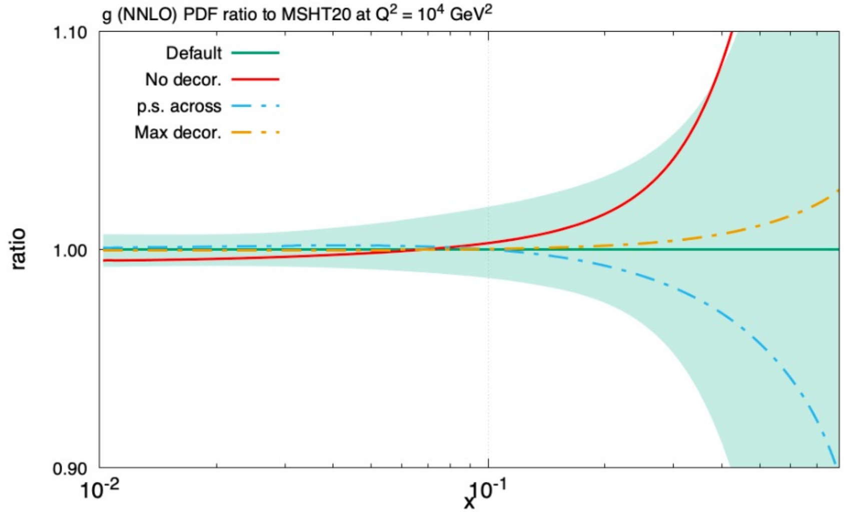
- Detailed information on both covariance and nuisance parameter representations for experimental errors is critical for full exploitation of data in PDF determinations
- Critical to Constrain m_t, α_s, g correlations

Highlights of EF03 activities: Top in PDFs (jointly with EF06)

- The role of top quark observables in PDFs: MSHT2020: Robert Thorne

Include all our recent LHC data updates in the fit at NNLO (for default $\alpha_S(M_Z^2) = 0.118$).

	no. points	NNLO $\chi^2/N_{\rm pts}$
D0 W asymmetry	14	0.86
$\sigma_{t\bar{t}}$ Tevatron +CMS+ATLAS $7, 8\mathrm{TeV}$	17	0.85
LHCb 7+8 TeV $W+Z$	67	1.48
LHCb 8 TeV e	17	1.54
CMS 8 TeV W	22	0.58
ATLAS 7 TeV jets $R=0.6$	140	1.59
CMS 7 TeV $W+c$	10	0.86
ATLAS 7 TeV W, Z	61	1.91
CMS 7 TeV jets $R=0.7$	158	1.11
ATLAS 8 TeV Zp_T	104	1.81
CMS 8 TeV jets	174	1.50
ATLAS 8 TeV $t\bar{t} \rightarrow l+$ j single-diff	25	1.02
ATLAS 8 TeV $t\bar{t} \rightarrow l^+l^-$ single-diff	5	0.68
ATLAS 8 TeV high-mass Drell-Yan	48	1.18
ATLAS 8 TeV $W^{+,-}+\mathrm{jet}$	32	0.60
CMS 8 TeV $(d\sigma_{t\bar{t}}/dp_{T,t}dy_t)/\sigma_{t\bar{t}}$	15	1.50
ATLAS 8 TeV W^+, W^-	22	2.61
CMS 2.76 TeV jets	81	1.27
CMS 8 TeV $t\bar{t}\, y_t$ distribution	9	1.47
ATLAS 8 TeV double differential Z	59	1.45
Total, LHC data	1328	1.33
Total, all data	4363	1.17



Effects on PDFs of different treatments of systematic uncertainties: no decorrelation, parton shower across, max. decorrelation

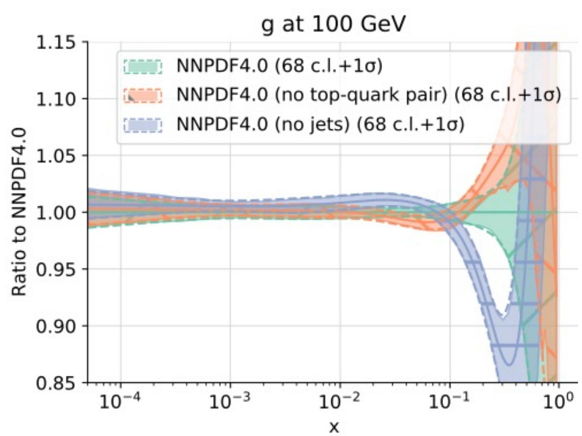
Fit quality generally good. Relatively poor χ^2 values for some sets seemingly observed by other groups, rectified by treatment of correlated uncertainties.

Highlights of EF03 activities: Top in PDFs (jointly with EF06)

- The role of top quark observables in PDFs: NNPDF: Emanuele Nocera

NNPDF4.0: more LHC data

Dataset	$N_{\rm dat}$	$\chi^2_{4.0}$
CMS $\sigma_{tt}^{\rm tot}$ 5 TeV	1	0.54
ATLAS $\sigma_{tt}^{\rm tot}$ 7 TeV	1	1.59
CMS $\sigma_{tt}^{\rm tot}$ 7 TeV	1	1.06
ATLAS $\sigma_{tt}^{\rm tot}$ 8 TeV	1	0.02
CMS $\sigma_{tt}^{\rm tot}$ 8 TeV	1	0.26
ATLAS $\sigma_{tt}^{\rm tot}$ 13 TeV (139 fb^{-1})	1	0.51
CMS $\sigma_{tt}^{\rm tot}$ 13 TeV	1	0.06
ATLAS ℓ+j 8 TeV $(1/\sigma d\sigma/dy_t)$	4	3.22
ATLAS ℓ+j 8 TeV $(1/\sigma d\sigma/dy_{t\bar{t}})$	4	3.77
ATLAS 2ℓ 8 TeV $(1/\sigma d\sigma/dy_{t\bar{t}})$	5	1.61
CMS ℓ+j 8 TeV $(1/\sigma d\sigma/dy_{t\bar{t}})$	9	1.23
CMS 2ℓ 8 TeV $(1/\sigma d\sigma/dy_t dm_{t\bar{t}})$	16	1.03
CMS ℓ+j 13 TeV $(d\sigma/dy_t)$	11	0.63
CMS $t\bar{t}$ 2ℓ 13 TeV $(d\sigma/dy_t)$	10	0.52
ATLAS dijets 7 TeV, $R=0.6$	90	2.15
CMS dijets 7 TeV	54	1.81
ATLAS incl. jets 8 TeV, $R=0.6$	171	0.69
CMS incl. jets 8 TeV	185	1.19
Total	4618	1.16

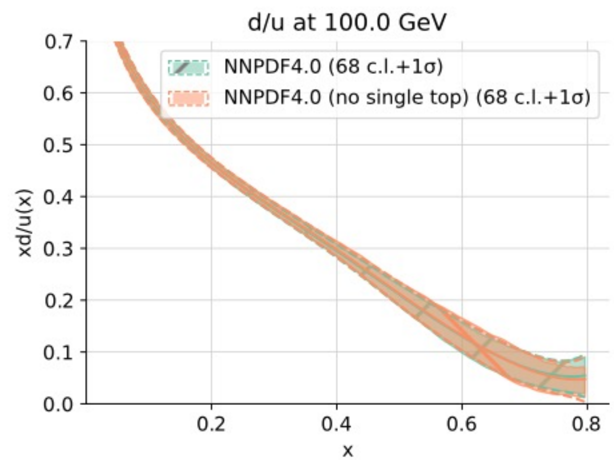


Dataset significantly extended in NNPDF4.0 (top and jets)

top: 40 data points more than NNPDF3.1

jet: 336 data points more than NNPDF3.1

Competing pulls of top and jets



Single top production not yet precise enough to constrain PDF

Highlights of EF03 activities: Top and HF in PDFs (with EF06)

- Simultaneous extraction of alphas and m_{top} from tt differential distributions: Matthew Lim

- 8 TeV data from ATLAS and CMS collected in Run 1
- Differential distributions of tops reconstructed from lepton+jets analyses, common binning
- Transverse momentum p_t^T, invariant mass $M_{t\bar{t}}$, single and pair rapidities y_t,$y_{t\bar{t}}$
- Absolute and normalised distributions—separate data sets from ATLAS, only normalised from CMS (absolute inferred)
- Theory values of $\sigma_{t\bar{t}}$ calculated using `top++2.0` at NNLO with NNLL resummation of soft gluons

- Find noticeable differences between
  - ATLAS and CMS
  - Different PDF choices
  - Different distributions

  indicating large sensitivity to all factors—data, PDF and kinematics.
- In order to reconcile differences/arrive at best values,
  - Restrict $0.115 \leq \alpha_s \leq 0.120$ and $170.0 \leq m_t \leq 175.0$ GeV ($\pm \sim 3\sigma$ around world average);
  - Perform a weighted average over various extractions.

- 'Best' value from combining two ATLAS distributions and averaging CT14 results.
- $\alpha_s = 0.1159^{+0.0013}_{-0.0014}$, $m_t = 173.8^{+0.8}_{-0.8}\mathrm{GeV}$.
- Prospects for future inclusion of theory uncertainties due to MHO.

- Most pragmatic way to include effects due to MHOU is *alla* NNPDF.
  - Assume Gaussian uncertainties, construct a theory covariance matrix.
- More sophisticated approach (see Tackmann, Les Houches 2019):
  - Regard missing higher order terms as nuisance parameters.
  - $\sigma = c_0 + \alpha_s(\mu)[c_1 + \alpha_s(\mu)c_2 + \ldots]$
  - In the simplest case c_2 is a number, more generally a function.
  - Correct correlations obtained, when multiple parameters involved CLT implies total theory uncertainty is Gaussian.

Highlights of EF03 activities: SM predictions

- EW higher order calculations for top quark and heavy flavor production at lepton colliders: Emi Kou
- A detailed comparison of QCD modelling in pp → ttW production: G. Bevilacqua, H. Bi, F. Febres-Cordero, H.B. Hartanto, M. Kraus, J. Nasufi, L. Reina, M. Worek LoI

Presented at this workshop:

- Soft gluons in top processes (tt and tW) at high energies: Nikolaos Kidonakis

Highlights of EF03 activities: SM predictions

- Soft gluons in top processes (tt and tW) at high energies: Nikolaos Kidonakis

Soft-gluon corrections

partonic processes (in general $2 \to n$)

$$f_1(p_1) + f_2(p_2) \to t(p_t) + X$$

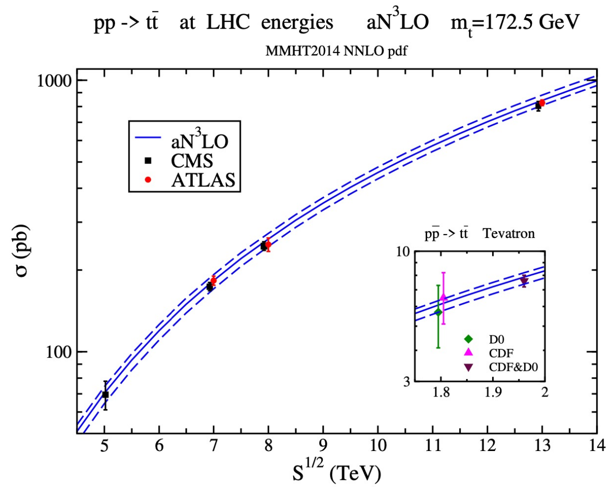
define $s = (p_1 + p_2)^2$, $t = (p_1 - p_t)^2$, $u = (p_2 - p_t)^2$ **and** $s_4 = s + t + u - p$

At partonic threshold $s_4 \to 0$

Soft corrections $\left[\frac{\ln^k(s_4/m_t^2)}{s_4}\right]_+$ **with** $k \le 2n-1$ **for the order** α_s^n **corre**

Resum these soft corrections $\to$ **finite-order expansions-no prescripti**

Approximate NNLO (aNNLO) and N^{3}LO (aN^{3}LO) predictions
for cross sections and differential distributions (single and double)



soft-gluon corrections dominant at LHC for total & differential cross sections

$t\bar{t}$ at high energies - preliminary results ($\mu = m_t$, same pdf)

	14 TeV	20 TeV	30 TeV	40 TeV	50 TeV	100 TeV
NLO/LO	1.50	1.51	1.52	1.53	1.54	1.58
aNLO/NLO	0.99	0.98	0.97	0.96	0.95	0.92
NNLO/NLO	1.11	1.11	1.11	1.11	1.11	1.10
aNNLO/NNLO	1.00	1.00	0.99	0.99	0.99	0.98
aN^{3}LO/NNLO	1.03					

where

aNLO = LO + soft-gluon NLO corrections

aNNLO = NLO + soft-gluon NNLO corrections

aN^{3}LO = NNLO + soft-gluon N^{3}LO corrections

Highlights of EF03 activities: Top physics at a muon collider

Presented at this workshop:

- Top quark physics at a muon collider: Tobias Thiel
- Precision studies at a muon collider: Patrick Meade (jointly with EF01/EF04)

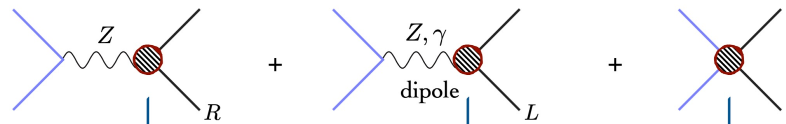
Highlights of EF03 activities: Top physics at a muon collider

- Top quark physics at a muon collider: Tobias Thiel

Top compositeness at future lepton colliders

- Multiple operators enter top pair production

$\mathcal{M}_{\ell^+\ell^-\to t\bar{t}} \sim$ + +



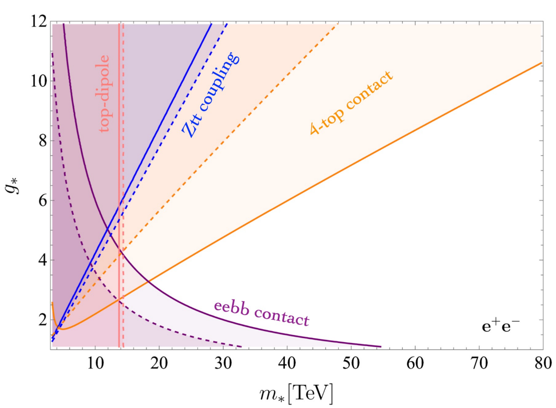
$$\frac{g_*^2}{m_*^2}(H^\dagger D_\mu H)(\bar{t}_R\gamma^\mu t_R) \qquad \frac{y_t g}{m_*^2}\bar{q}_L H\sigma_{\mu\nu}W^{\mu\nu}t_R \qquad \frac{c_{te}}{m_*^2}(\bar{e}_R\gamma_\mu e_R)(\bar{t}_R\gamma^\mu t_R)$$

$$\sim \frac{g_*^2}{m_*^2}m_W^2 \qquad \sim \frac{g^2}{m_*^2}m_t\sqrt{s} \qquad \sim \frac{g_*^2}{m_*^2}s$$

At high energies, contact interactions dominate

Top compositeness at ILC and CLIC

High c.o.m. energies great advantage in (indirectly) probing most of parameter space.



$\frac{m_*}{g_*} > 7.7$ TeV

[Banelli et al. 2010.05915]

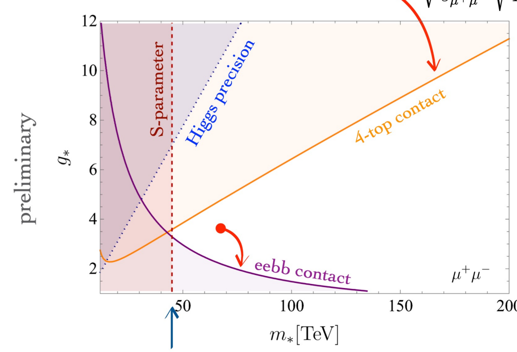
$\frac{m_*}{g_*} > 4.3$ TeV

[de Blas et al. 1902.00134]

Top compositeness at μ-Collider

Same conclusion at a high-energy muon collider, with larger reach!

$\sqrt{s_{\mu^+\mu^-}} = 10\,\text{TeV}$ $\quad L_{\mu^+\mu^-} = 10\,/\text{ab}$ $\quad \times\sqrt{\frac{s_{\text{CLIC}}}{s_{\mu^+\mu^-}}}\sqrt{\frac{L_{\text{CLIC}}}{L_{\mu^+\mu^-}}}$ (statistically dominated errors)



[Buttazzo et al. 2012.02769]

$\frac{m_*}{g_*} \gtrsim 18$ TeV

$\frac{m_*}{g_*} \gtrsim 6.4$ TeV

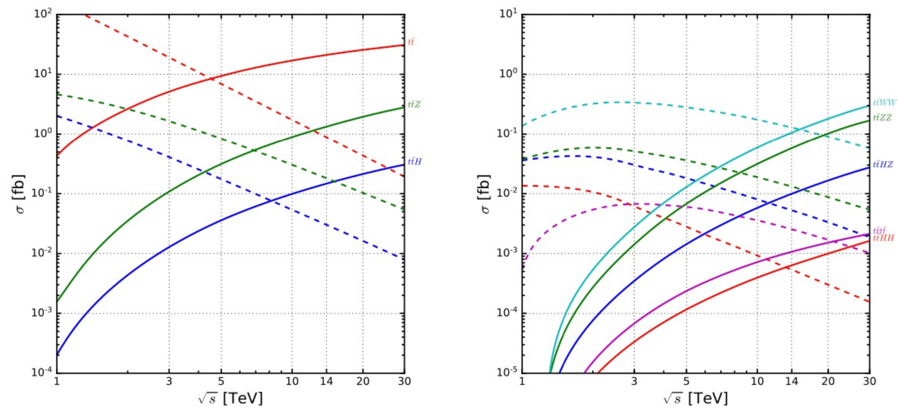
[Han et al. 2008.12204]

Main assumption is that uncertainty remains statistically dominated.

Highlights of EF03 activities: Top physics at a muon collider

- Precision studies at a muon collider: Patrick Meade (jointly with EF01/EF04)

Vector boson fusion at multi-TeV muon collider: Antonio Costantini, Federico De Lillo, Fabio Maltoni, Luca Mantani, Olivier Mattelaer, Richard Ruiz and Xiaoran Zhao, arxiv:2005:10289



(a) (b)

Figure 3. W^+W^- fusion (solid) and analogous s-channel annihilation (dashed) cross sections σ [fb] for (a) $t\bar{t}X$ and (b) $t\bar{t}XX$ associated production as a function of collider energy $\sqrt{s}$ [TeV].

s-channel annihilation rates categorically scale and decrease with collider energy at least as $\sigma \sim 1/s$, when collider energies are far beyond kinematic threshold. This is contrary to VBF processes where cross sections mildly increase with collider energy at least as a power of $\log(s/M_W^2)$, in the high energy limit.

Other EF03 activities

- Prospects for the 4top Process: Stephen Wimpenny
- ttW production: a very complex process: Marcos Miralles Lopez, Maria Moreno Llacer
- Precise predictions for top-quark flavor-changing neutral interactions at future lepton colliders: Gauthier Durieux, Stefano Frixione, Benjamin Fuks, Hua-Sheng Shao, Liaoshan Shi, Marco Zaro, Cen Zhang, and Xiaoran Zhao LoI
- Probing top quark FCNC couplings tqγ, tqZ at future e+e− collider: Peiwen Wu LoI
- Top quark physics at FCC-ee: J. Andrea, P. Azzi, B. Fuks LoI
- Top-Quark and Electroweak Physics at LHeC and FCC-eh: N. Armesto, O. Behnke, D. Britzger, O. Cakir, M. Klein, C. Schwanenberger, H. Spiessberger LoI
- Study on the discovery potential of all-hadronic searches for ttbar resonances at future colliders: Johan Bonilla, Robin Erbacher, Christine Mclean, Meg Morris, Salvatore Rappoccio, A.C. Malik Williams LoI

Final remarks

- Many opportunities to contribute to Top/HF production physics
  - So far most input from ILC and HL-LHC,
  - Top physics potential talks from FCC-ee, LHeC and FCC-eh
  - Study top at other colliders (new: muon collider)
  - Need many more HL-LHC studies to explore full program
  - Across topical group boundaries
- We invite you to contribute to top/HF production studies
  - EF03 wiki page at https://snowmass21.org/energy/heavy_flavour
  - Email the conveners: schwier@msu.edu, dw24@buffalo.edu
  - Mailing list SNOWMASS-EF-03-TOP_HEAVY-FLAVOR@FNAL.GOV
  - Looking for presentations at our biweekly meetings
- Informal (incomplete) list of projects, possible collaborations, open questions, etc.https://docs.google.com/document/d/17aPp9XpJAImmPlnPNtgV21rG2zEiFS2IHkO-ooC4rcQ
- See EF03 wiki page for full list of Letters of Interest